REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE 6/02

3. REPORT TYPE AND DATES COVERED
Final Progress Report – 9/1/96 – 9/31/01

4. TITLE AND SUBTITLE
Photonic Band Engineering

5. FUNDING NUMBERS
DAAH04-96-1-0389

6. AUTHOR(S)
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20021021 044

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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REPORT NUMBER
KD8K-Final-0900

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
35875-PH-MUR
.164

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Scientists at UCLA, Caltech, and Polytechnic University have developed a new concept in Electromagnetics called "Photonic Bandgaps" that permits unprecedented control of Electromagnetic Waves, at both radio frequencies, and optical frequencies. This new paradigm of Electromagnetics is based on Nature's design for semiconductor crystals, but it is a crystal structure that is artificially engineered for electromagnetic waves rather than for electron waves.

Beginning in 1996, new frontiers in the engineered control of electromagnetic waves have emerged from this design paradigm. For example, the very tiniest, most miniaturized electromagnetic cavity ever created was engineered, and demonstrated, under this MURI; trapping optical energy in the smallest volume ever achieved. This world's most tiny light trap was also made into the most miniaturized laser ever made, occupying a volume smaller than a cubic wavelength.

At the same time this MURI advanced the electromagnetic bandgap concept into microwaves and radio waves that are so important for military systems. This required new concepts that permitted the bandgap structure to be much smaller than the electromagnetic wavelength. As in the optical version of photonic crystals, these electromagnetic bandgaps permit unprecedented control over radio frequency electromagnetic waves. For example new antenna structures have been invented that permit near field control over radio emissions from antennas, so that the hand-held radio transmitters can be more efficient.

14. SUBJECT TERMS
Photonic Crystal, Photonic Band Gap, Nano-laser, Photonic Band Structure, High Impedance Ground Plane

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Photonic Band Engineering

Final Progress Report

Eli Yablonovitch

Period covered: 9/1/96 - 09/31/01

U.S. Army Research Office

DAAH04-96-1-0389

University of California, Los Angeles

Final Report

Photonic Band Engineering MURI

UCLA / Caltech / Polytechnic

Sept. 1996—Sept. 2001

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There were a number of accomplishments by our joint UCLA/Caltech/Polytechnic University team, in various areas of photonic crystal applications in electromagnetics:

(a) Our team established the validity of using 2-dimensional thin film slab photonic crystals, as a viable alternative to 3-dimensional photonic crystals. We proved that index confinement could perform adequately in the third dimension, greatly simplifying the technological demands of photonic crystals. Indeed, this 2-dimensionality opens up the possibility of creating photonic crystals by straightforward photo-lithography that is very much in the mainstream of conventional technology. This is expected to lead to commercialization of optical photonic crystal structures much faster than had been originally expected.

Among the specific accomplishments in 2-d thin film slab photonic crystals are:

(i) The smallest electromagnetic cavity every made.

(ii) The smallest laser ever made.

(iii)The demonstration of spontaneous emission enhancement and suppression in 2-d thin-film slab photonic crystals.

(b) Our team demonstrated that long wavelength low frequency photonic crystals were practical, and that they could be quite compact. The spatial period of these structures could be much smaller than the vacuum electromagnetic wavelength. This was quite a surprising conclusion, that emerged when the effect of LC resonances was taken into account. LC resonators can be much smaller than a wavelength, yet they have a powerful influence on electromagnetic waves. In effect then the periodicity of a photonic crystal is determined by the size of the LC resonators, rather than by the electromagnetic wavelength, as had been believed up until then. When the LC resonators are periodically distributed in space, interesting and compact electromagnetic bandgap structures result.

As an example, a two dimensional array of LC resonators above a conventional metallic ground plane results in a high impedance ground plane, that has novel applications in the control of electromagnetic waves. This can be useful for high precision GPS antennas, for example.

Among the specific accomplishments at UCLA and/or Caltech, we did the following:

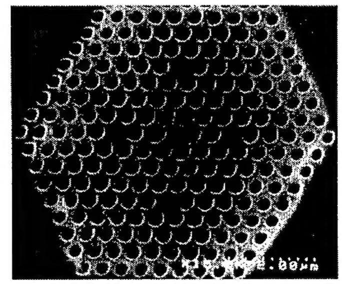

Figure 1: A thin film 2-dimensional photonic crystal slab, incorporating 5 coupled nano-cavities.

- Designed and fabricated photonic crystal membrane microlasers which work at room temperature,
- optimized the necessary microfabrication instruments and procedures to define 2-D photonic bandgap crystals for use in the near-IR and visible wavelength range. Photonic crystals have been succesfully fabricated in the InGaAs/InP, GaAs/AlGaAs, InGaP/InGaAlP, and GaN/AlGaN materials systems. In a collaboration with the Army Research Laboratory, diffractive optical lenses were also fabricated using these techniques.
- developed Finite Difference Time Domain (FDTD) computer code for the calculation of field intensities and the calculation of cavity Qs in three dimensional photonic crystal cavity structures, and to evaluate their spontaneous emission coupling factors.
- designed and modeled photonic crystal geometries which were optimized to define the smallest resonant cavities with high Qs (above 15,000).
- compared the spontaneous emission coupling efficiencies of single-defect photonic crystal microcavities with those in whispering gallery mode lasers and optimized the design of the microlaser structure with a 86% spontaneous emission coupling factor.
- fabricated microcavities and new in-plane optically pumped photonic crystal lasers operating at 1.55 μm in InGaAs/InP and passive resonator filters in GaAs/AlGaAs.
- measured the optical response of single defect photonic crystal microcavities as well as larger (2-10 μm diameter) photonic crystal lasers.
- measured luminescence intensities as function of lattice parameter and observed temperature tuning of the photonic bandgap in 2-D InGaAsP photonic crystals.
- measured bend losses and optimized the design in 2-D photonic crystal waveguides in silicon on insulator material.
- Constructed photonic crystal cavities in quantum dot material to examine these structures for strong coupling experiments.
- Fabricated multi-wavelength photonic crystal laser arrays in which the spectrum was lithographically tuned from 1.45 to 1.6 microns on the same chip
- Designed and fabricated ultra-small cavities which support only two modes and in which all-optical switching between these modes could be demonstrated.
- Designed and fabricated single mode photonic crystal waveguides and measured bend losses of light through sharp bends.
- Using photonic crystals as mirrors, we have designed a new family of high-Q cavities by using finite difference time domain calculations.
- We have designed devices in which light can be switched from one mode to another and

developed a waveguide converting all-optical switch.

- We have developed designs for photonic crystal cavities which will function with quantum cascade material.
- We have fabricated waveguides with sharp bends and show efficient light guiding around sharp corners at 1.55 μm in $Si/SiO_2/Si$ (SOI) slab waveguides. We have also mapped the modes supported in these waveguides and fitted our measurements to our models.
- We have designed photonic crystal nanocavities with Er-dopants as active light sources.
- We have designed and measured new optical cavity geometries to control the emission direction, tuning wavelength, polarization and mode structures and Qs within photonic crystal cavities.

One of the unique features of active photonic crystal cavities, which arises from their ability to limit the number of modes supported within the laser, is the ability to build high contrast modulators. Figure 2 shows an example of such a single defect photonic crystal cavity, which supports both shallow acceptor modes as well as deep donor modes within the same cavity. Depending on the diameter of the pump beam, (shown on the left-hand side of the figure), we find that different modes are excited, and these in turn exhibit different spectra. Finite-difference time-domain simulations of the expected geometric distribution of the field intensities

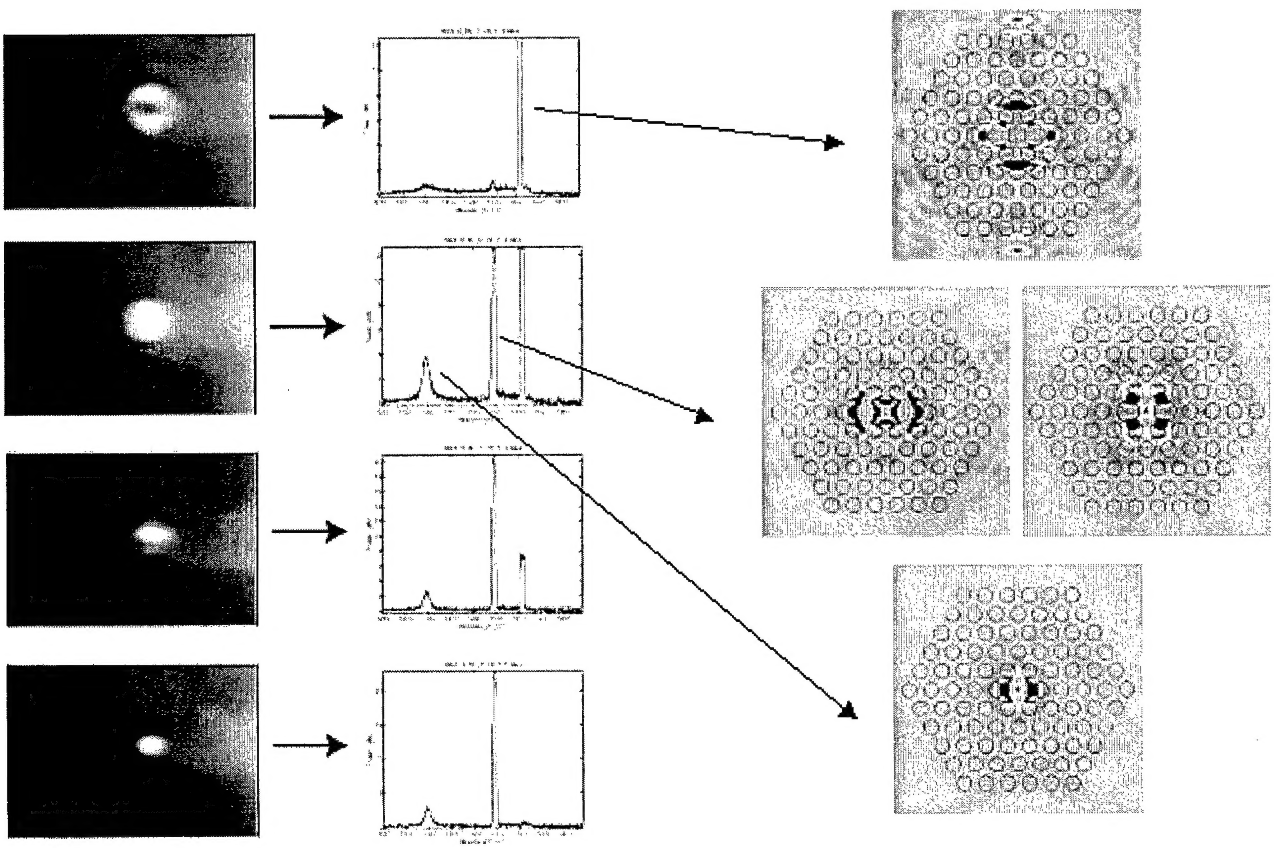

Figure 2: A nano-cavity laser that can lase at donor modes as well as acceptor modes.

within these modes are also shown, and the relative overlap of the pump beam with the expected mode geometries matches well to the observations.

We have also demonstrated electrically and optically pumped multi-wavelength nanocavity lasers, modulators and detector arrays in which lithography is used to define the precise spectral response of each element. We also expect to use the high fields within optical nanocavities by filling the voids of the photonic crystals with nonlinear materials. In the future, we will use these nonlinearities and high fields to define tunable nanocavity lasers, detectors, routers, gates and spectrometers for wavelength and time division multiplexing applications.

Technology Transfer:

The goal of this MURI was to take the photonic crystal concept out of the laboratory into specific practical applications.

In addition to the large number of papers that were published there were a number of patents that were developed. A few of these patents have been licensed to startup companies that have paid significant licensing fees, and they are now dedicated to commercializing some these ideas to emerge from this MURI.

It appears that nano-photonics, that includes photonic band engineering is now rushing headlong out the laboratory, and into commercialization for miniaturized opto-electronic circuits.

In addition, there appears to be great interest in using some of the photonic band engineering ideas in various wireless applications, that are important to Defense, but also important to the commercial world, where taking everything wireless is expected to be a MACRO trend for the next 20 years.

Impact:

The entire field of photonic crystals was aided at a critical point in its development by this MURI. As a result, this topical area of photonic crystal research is more lively than ever, occupying a greater and greater fraction of annual meetings such as the CLEO, the Conference on Lasers and Electro-Optics.

Another way of measuring impact is that this MURI spawned fully three startup companies:

Two in antenna design for wireless electromagnetics:

Ethertronics, Inc.	http://www.ethertronics.com/
Etenna, Inc.	http://www.etennacorp.com

and one in Nano-photonics:

Luxtera, Inc.	http://www.luxtera.com/

This MURI produced world leading research, that culminated in numerous invited presentations in scientific conferences. Indeed, in this year (2002) alone, there will be three international conferences dedicated to the topic of photonic crystals. Many of the papers to be presented at those conferences are outgrowths of the research done in this Photonic Band Engineering MURI.

The work did require an unusual integration of computational electromagnetics and opto-electronic device fabrication. There were strong teams at the individual Universities, and there was a lot of sharing of equipment, designs, software and samples.

The wireless electromagnetics work is expected to lead to new innovative designs for antenna structures, made possible in large part by the recognition of the power of LC resonators to control electromagnetic waves. The most immediate application will be to high precision GPS applications, and some work was done to achieve that objective.

The nano-photonic work is leading to a new type of integrated circuit, in which optical components are miniaturized down to the half wavelength level. This is expected to enable optical and electronic components to be fabricated together and to sit side by side in future integrated circuits. Such WDM opto-electronic integrated circuits are expected to impact military systems, and the research and development for this purpose is now being supported by DARPA's WDM program.

Educational Impact:

A number of students became educated, got their Ph.d. degrees and have gone on to excellent jobs in leading industrial and government research labs, as well as in the top Universities in the nation.

Photonic Band Structure Engineering Final Technical Report:
Period from September 1996 – October 2001
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142. "Curl Antennas over Electromagnetic Band-Gap Structures: A Low Profiled Design for CP Applications," Fan Yang and Yahya Rahmat-Samii, *APS Symposium*, July 2001.

143. "Grand Challenges in Analyzing EM Band-Gap Structures: An FDTD Technique based on the Split-Field Approach," Hossein Mosallaei and Yahya Rahmat-Samii, *APS Symposium*, July 2001.

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146. "A Novel Anisotropic Uniplanar Compact Photonic Band-Gap (UC-PBG) Ground Plane," C. Caloz, C. -C. Chang, and T. Itoh, *European Microwave Conference*, London, September, 2001.

Accepted for Publication

1. "Dielectric Relaxation in Ceramics with Intragrain Concentration Gradient," I. Lubomirsky, Y-W. Tzu, F. De Flaviis and O.M. Stafsudd, Phys. Rev. B.

2. “Properties of two-dimensional metallic photonic crystals,” K. M. Leung and Y. Qiu, Phys. Rev. B.
3. “The Influence of Barium Carbonate Contamination on Dielectric Loss in Barium Titanate Ceramics,” I. Lubomirsky, Tzu Yu Wang and Oscar M. Stafsudd.
4. “Critical coupling and its control in optical waveguide-ring resonator systems,” A. Yariv, Accepted for publication to *Electronics Letters*.
5. “Design of photonic crystal microcavities for cavity QED,” J. Vuckovic, M. Loncar, H. Mabuchi and A. Scherer, *submitted to Phys. Rev. A.*
6. "Light Coupling Mechanism of Quantum Grid Infrared Photodetectors", J. Mao, A. Majumdar, K.K. Choi, D.C. Tsui, K. M. Leung, C. H. Lin, T. Tamir and G. A. Vawter, *submitted to Appl. Phys. Lett.*
7. "Modal Transmission-Line Theory of Three-Dimensional Periodic Structures Having Arbitrary Lattice Configurations", Chung-Hsiang Lin, K. M. Leung, and T. Tamir, *submitted to J. Opt. Soc. Am. A.*
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9. “A Low-Profile Circularly Polarized Curl Antenna Over an Electromagnetic Bandgap Surface,” Fan Yang, Y. Rahmat-Samii, *submitted to Microwave and Opt Tech. Lttrs., 2001.*
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12. “Periodic PBG and Effective Dielectric Materials in Electromagnetics: Characterization and Applications in Nanocavities and Waveguides,” Hossein Mosallaei and Yahya Rahmat-Samii, 2001.
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14. “Fractal FSS: Various Self-Similar Geometries Used for Dual-Band and Dual-Polarized FSS,” J. Gianvitorio, Y. Rahmat-Samii, J. Romeo, *submitted to IEEE, 2001.*

List of Scientific personnel supported by this project and honors/awards/degrees received during this reporting period:

UCLA

Professors: Eli Yablonovitch, Nicolaos Alexopoulos, Yahya Rahmat-Samii, Tatsuo Itoh, Oscar Stafsudd

Post Docs: David Chen, Roberto Coccioli, Harry Contopanagos, Ivair Gontijo, Chul-Sik Kee, Kangwook Kim, Hideo Kosaka, O'Dae Kwon, Chryssoula Kyriazidou, Igor Lubomirsky, Gregory Poilasne, Yongxi Qian, Sebastian Rowson, Hans Robinson, Rutger Vrijen

Students: Ivan Alvarado, Alon Barlevy, Misha Boroditsky, Romulo Broas, M. Chatterji, Joseph Colburn, J. Gianvittorio, Zachary Hepner, Thomas Jun, Z. Li, Khang Le, H. Mossallaei, Adit Narasimha, Deepak Rao, Dan Sievenpiper, Jaione Tirapu-Azpiroz, Tzu-Yu Wang Fei-Ran Yang, Lijun Zhang, Wenyu Zhang

Caltech

Professors: Axel Scherer, Amnon Yariv

Post Docs: Thomas Krauss, John O'Brien, Reginald Lee, Oskar Painter, Jelena Vuckovic, Joyce Wong, Yong Xu

Students: David Barsic, T. R. Chen, Chuan-Cheng Cheng, Brian D'Urso, John Choi, Will Green, L. Gunn, Ali Husain, Ben Kitzke, Reynold Johnson, Marko Loncar, T. Yoshie

Visitor: T. Doll,
Staff: Ali Ghaffari, Reynold Johnson

Polytechnic

Professor: Ming Leung

Post Doc: Chung-Hsiang Lin

Honors/Awards

T. Itoh received 1998 Shida Award from Ministry of Post and Telecommunications, Japanese Government for his pioneering work on Active Integrated Antennas for Microwave and Millimeter Waves.

Y. Qian, F. R. Yang and T. Itoh received the Japan Microwave Prize for their paper "Characteristics of microstrip lines on uniplnar compact PBG ground plane", presented at

Asia Pacific Microwave Conference (APMC98), Yokohama, Japan, December 8-11, 1998.

Iterative Forum Second Prize for the paper: J. S. Colburn and Y. Rahmat-Samii, "Linear tapered slot antenna directivity improvement via substrate perforation", 1998 IEEE Antennas and Propagation Symposium, pp. 1176-1179, Atlanta, GA, June 1998.

1998 Distinguished Teacher Award, Polytechnic University: K. Ming Leung

Invited speaker at IEEE Terahertz Technology in Leeds, England to present microwave and millimeter wave applications of PBG in September 1998: T. Itoh

Japan Microwave Prize for the paper: "Characteristics of Microstrip Lines on a Uniplanar Compact PBG Ground Plane," Yongxi Qian, Rei-Ran Yang, and Tatsuo Itoh, 1998 Asia-Pacific Microwave Conference, Yokohama, Japan, December 8-11, 1998

Second Best Student Paper IEEE Award : Hossein Mosallaei and Yahya Rahmat-Samii, "Photonic Band-Gap (PBG) versus Effective Refractive Index: A Case Study of Dielectric Nanocavities," *APS Symposium*, July 2000.

Eli Yablonovitch received the Julius Springer Prize, 2001.

Invited Talk: Yahya Rahmat-Samii and Hossein Mosallaei, "Electromagnetic Band-Gap Structures: Classification, Characterization, and Applications," *IEE Symposium*, UK, Apr. 2001.

URSI Young Scientist Award: Hossein Mosallaei and Yahya Rahmat-Samii, "Characterization of Complex Periodic Structures: FDTD Analysis based on Sin/Cos and Split-Field Approaches," *URSI Electromagnetic Symposium*, May 2001.

List of Degrees/ Honors/Awards received

UCLA:
Hossein Mosallaei, PhD, 2001
Lijun Zhang, PhD, 2001
David Chen, PhD, 2000
Tzu-Yu Wang, PhD, 2000
Fei-Ran Yang, PhD, 2000
Chryssoula Kyriazidou, Ph.D, 1999
Dan Sievenpiper, PhD, 1999
Alon Barlevy, PhD, 1998
Joseph Colburn, PhD, 1998

Adithyaram Narasimha, MS, 2001
John Gianvitorio, MS, 2000

Wenyu Zhang, MS, 2000
Romulo Broas, MS, 1999
Zachary Hepner – MS, 1998

Caltech: Jelena Vuckovic, PhD, 2001
Yong Xu, PhD, 2001
Reginald Lee, PhD, 2000
Oskar Painter, Ph.D., 2000
Joyce Wong, PhD, 2000
John Choi, MS, 2000
Will Green, MS, 2000

Report of Invention:

U.S. Patent No. 5,739,796, Issued 04/14/98
Title: "Ultra-Wideband Photonic Band Gap Crystal Having Selectable and Controllable Band Gaps and Methods for Achieving Photonic Band Gaps," Louis J. Jasper, Jr., Lawrence Carin, and K. Ming Leung.

U.S. Patent No. 6,040,590, Issued 3/21/00
Title: "Semiconductor laser device with electrostatic control," Reginald Lee, John O'Brien, Oskar Painter, Axel Scherer, Yuanjian Xu, Amnon Yariv

U.S. Patent No. 6,215,134, Issued 4/10/01
Title: "Fabrication of Semiconductor Surface Lenses and Hemispheres," J. O'Brien, C.-C. Cheng, A. Scherer, A. Yariv, Y. Xu.

U.S. Patent No. 6,262,4985B1, Issued 07/17/2001
Title: "Circuit and Method for Eliminating Surface Currents on Metals," E. Yablonovitch, D. Sievenpiper.

Technology Transfer:

Ethertronics, Inc., Los Angeles
E-tenna Corporation, Maryland
Raytheon Systems Co., Los Angeles
Hughes Space and Comm, Los Angeles
Hewlett-Packard, Opto-electronics Div., San Jose
Hewlett-Packard Laboratories, Palo Alto
Rockwell International , Thousand Oaks
Ortel Corporation, Alhambra
Conexant, Newport Beach
Leica Geo-systems, Torrance
Corning Corp. Corning NY.

Among Federal Labs:

- Air Force Research Lab., Hanscom Field, Mass.
- Wright Paterson Air Force Base, Dayton Ohio
- Naval Research Lab, Washington DC,
- Army Research Lab, Adelphi MD
- US Army AMCOM, Huntsville AL